



# ***Quantifying Risk to California's Energy Infrastructure from Projected Climate Change***

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# *Quantifying Risk to California's Energy Infrastructure from Projected Climate Change*



- Background to study
  - PIER studies focus on climate risks to the general economy
  - State's energy infrastructure also directly at risk
  - Study has not formally begun.
  - Deliverables to include white paper this summer and report early next year
- This presentation
  - Overview of the methodology (Larry Dale)
  - Example of the methodology (Andre Lucena)
  - Damage metrics and data needs (Pete Larsen)



# Methodology Overview

1. What's covered?
  - Types of climate events
  - Energy infrastructure at risk
  - Time period
2. How to identify infrastructure at risk?
  - GIS mapping of climate and infrastructure.
  - Previous studies of some risks (fire and ocean level)
3. How to determine damage to infrastructure?
  - Energy and utility expert interviews
  - Data collection, analysis
  - Review of past studies
4. How to summarize damages?
  - Costs, Discounting, and Uncertainty
  - Outages?/Energy Output Measures
  - Adaptation Assumptions?
5. Principle data and analysis gaps
  - Data gaps--location and severity of extreme wind and flood events
  - Assembling expert panel

# AOGCMs; Emission Scenarios



## Stages

### I. Climate Change Impact

Precipitation

Sea Level

Temperature (air and water)

Wind

Gather information from different Institutions (*italic*)

### II. Types of climate events

(A) Inland Floods  
(*Scripps*)

(B) Coastal Inundation  
(*Pacific Institute*)

(C) Warmer Air and  
Water  
(*Scripps*)

(D) Wildfire  
(*Westerling*)

(E) High Winds and  
Tornadoes  
(*Scripps*)

Overlay climatic and infrastructure  
GIS information

### III. Identify infrastructure at risk

(1) Natural Gas  
Storage Tanks

(2) Natural Gas  
Pipelines

(3) Thermal Power  
Plants

(4) Transmission Lines

(5) Distribution Lines and  
Substations

Experts interviews, literature  
review, data analysis

Possible Indirect  
Effect (Outage)

### IV. Determine type of damage

(A1) Water Damage

(A2; B2) Water  
Damage, Outage

(B3) Water Damage,  
Outage  
(C3) Loss in Efficiency  
and Capacity

(C4) Transmission Loss  
(D4) Downed lines,  
Outage  
(E4) Downed lines,  
Outage

(A5) Downed lines, Downed  
Substations, Outage  
(D5) Downed lines, Outage  
(E5) Downed lines, Outage

Experts interviews, literature  
review, data analysis, energy  
modeling

### V. Summarize damages

(A1) Depreciated  
Replacement Costs,  
Adaptation Costs

(A2; B2) Depreciated  
Replacement Costs,  
Adaptation Costs,  
Outage Severity

(B3) Depreciated  
Replacement Costs,  
Adaptation Costs  
(C3) Extra Installed  
Capacity

(C4) Extra Installed  
Capacity  
(D4; E4) Depreciated  
Replacement Costs,  
Outage Severity

(A5, D5, E5) Depreciated  
Replacement Costs,  
Outage Severity

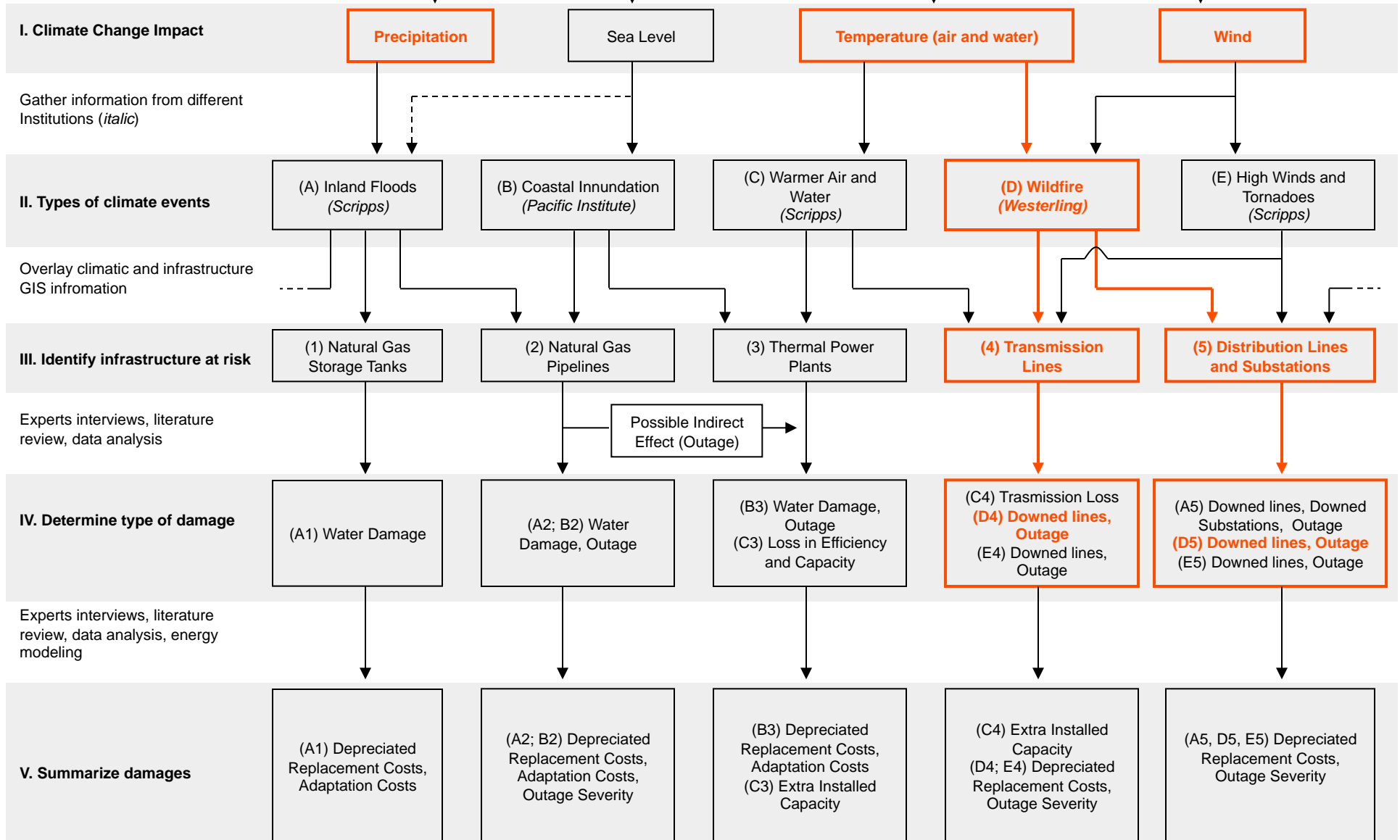


# Impacts: Methodology Examples

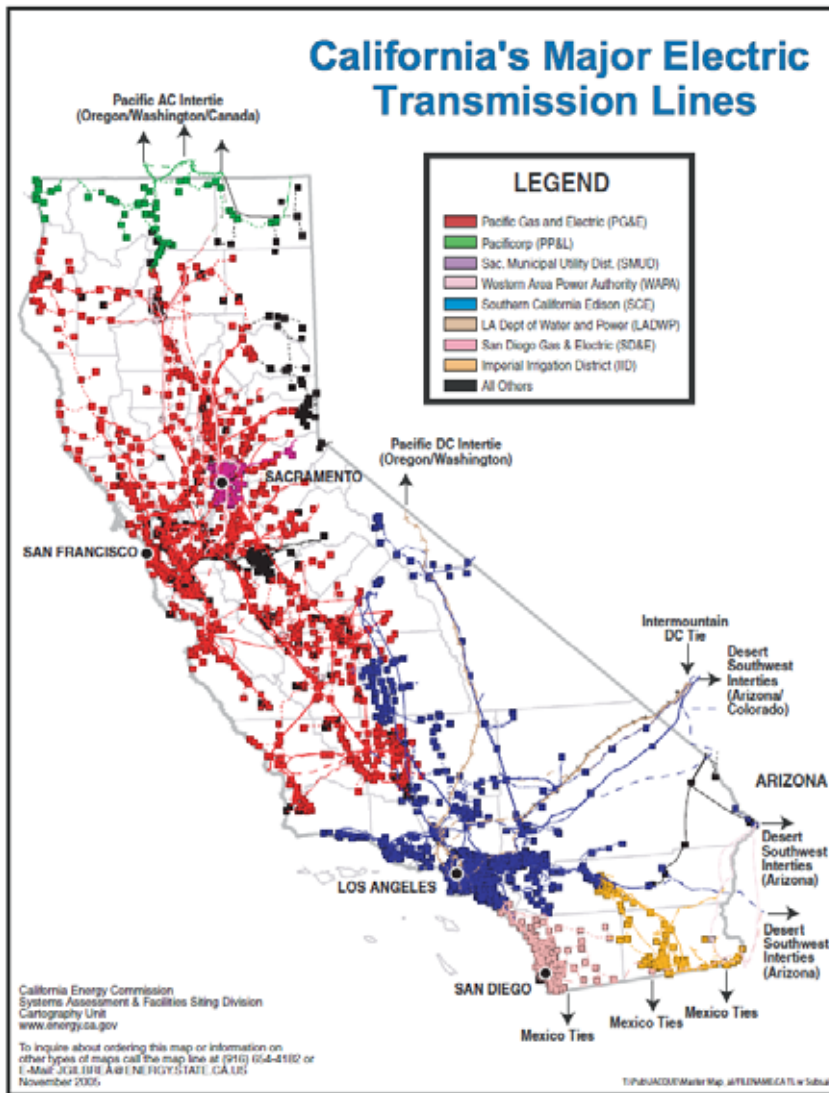
# AOGCMs; Emission Scenarios



## Fire Example

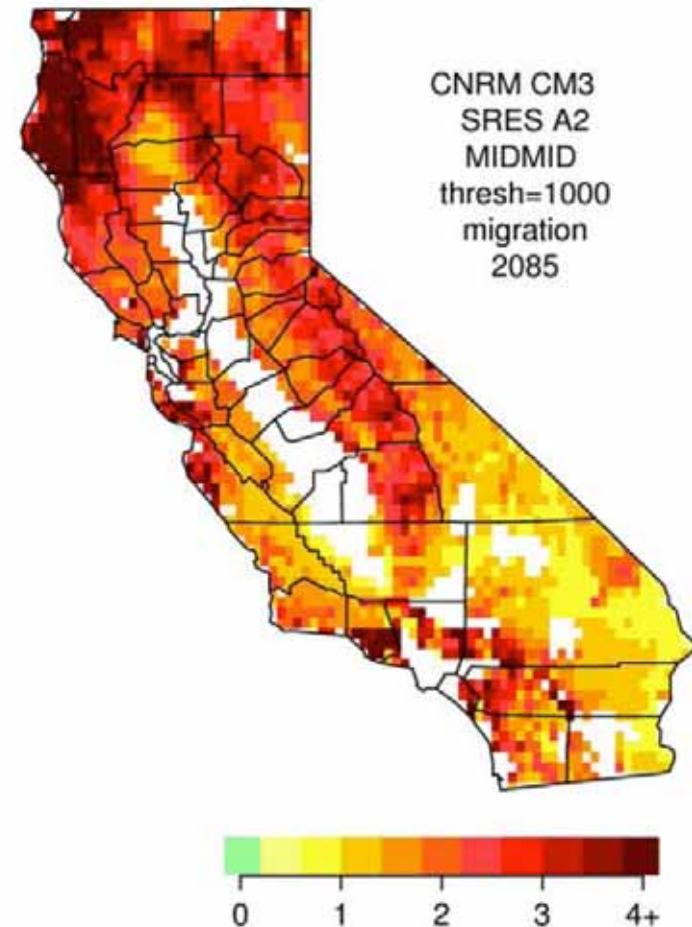


# GIS Crossing – Example: Wildfire



## 2085 Predicted Burned Areas (multiple of reference period)

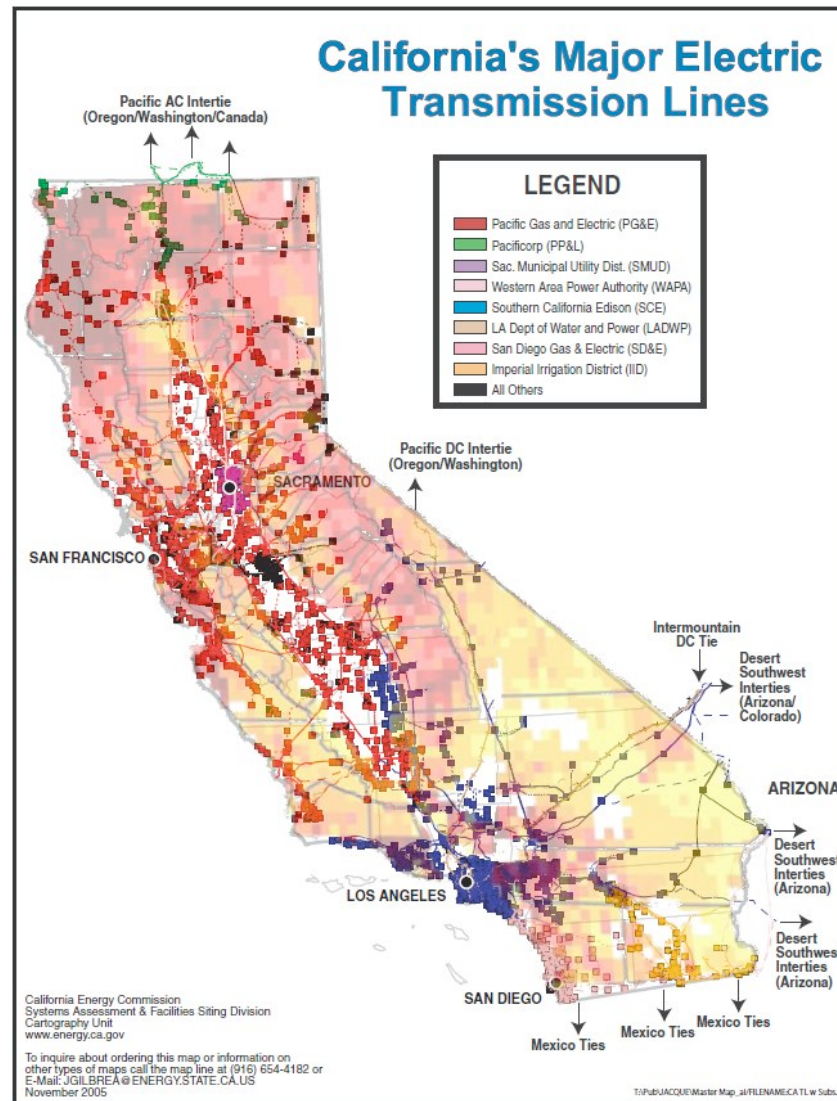
Source: Westerling et al. (2009)





# GIS Crossing

## Example: Wildfire vs. Transmission Lines

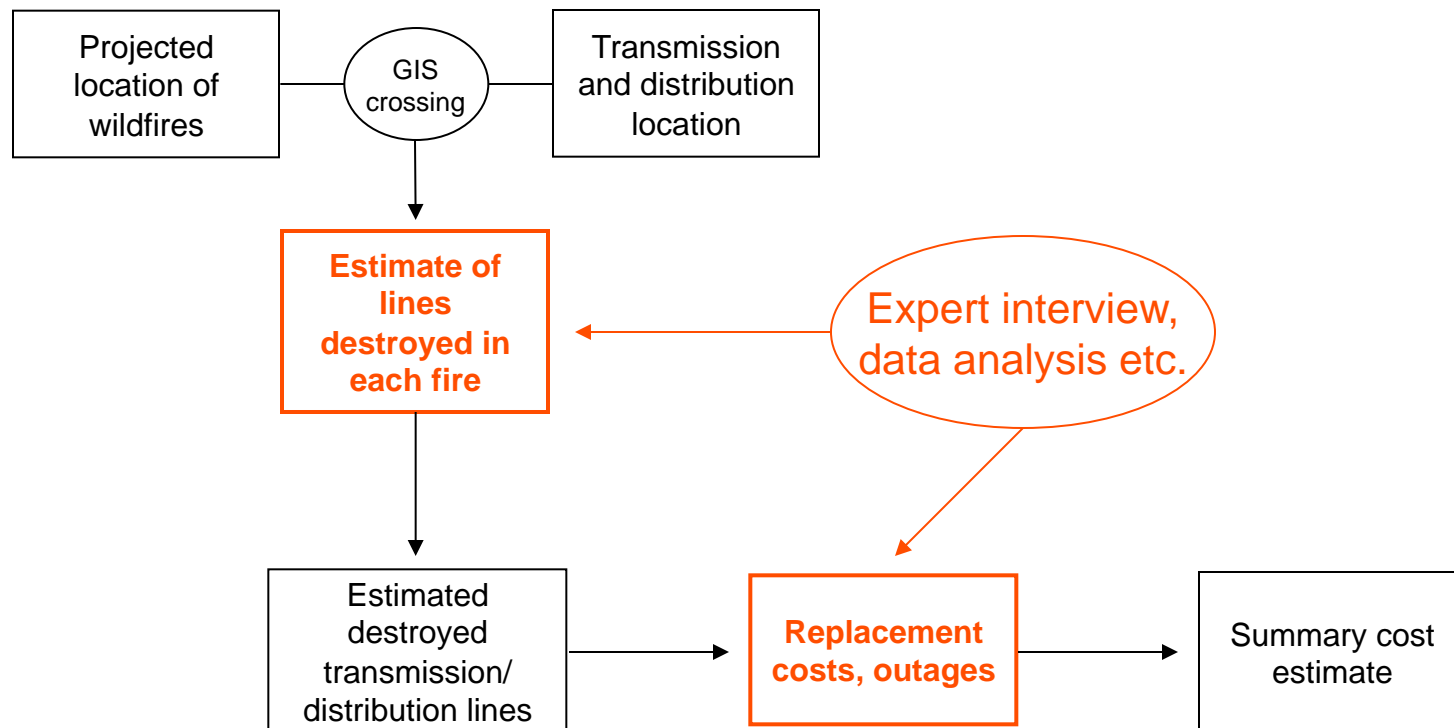




# Impacts of Increased Wildfire Activity on Transmission and Distribution Lines



- Similar methodology to Westerling and Bryant (2008)
  - Analyzed property damages due to wildfire



# AOGCMs; Emission Scenarios

## Temperature Example

### I. Climate Change Impact

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Sea Level

Temperature (air and water)

Wind

Gather information from different Institutions (*italic*)

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Overlay climatic and infrastructure GIS information

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(C4) Transmission Loss  
(D4) Downed lines,  
Outage  
(E4) Downed lines,  
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(A5) Downed lines, Downed  
Substations, Outage  
(D5) Downed lines, Outage  
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Experts interviews, literature  
review, data analysis, energy  
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(C3) Extra Installed  
Capacity

(C4) Extra Installed  
Capacity  
(D4; E4) Depreciated  
Replacement Costs,  
Outage Severity

(A5, D5, E5) Depreciated  
Replacement Costs,  
Outage Severity

# Warmer Air and Water Impacts on Power Plant Efficiency and Capacity

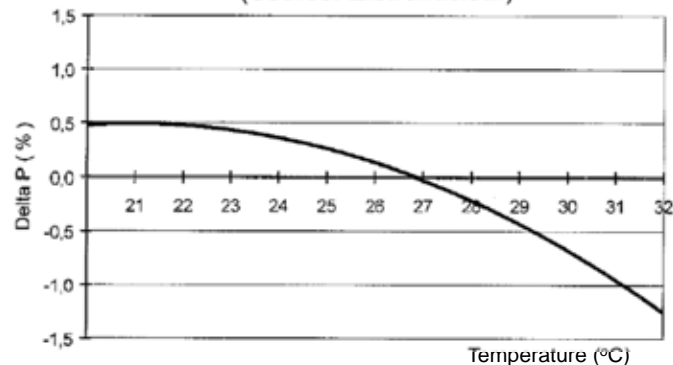


- GIS crossing: power plants location vs. projected temperature *variation*
- Finding a representative relationship between Air/Water temperature and thermal power plants conversion efficiency and capacity:
  - Information from utilities
  - Types/models of turbines
  - Level of aggregation (more than 300 natural gas power plants)
- RESULTS:
  - Loss in efficiency – lower electricity generation (MWh)
  - Loss in capacity – lower installed generating capacity (MW)

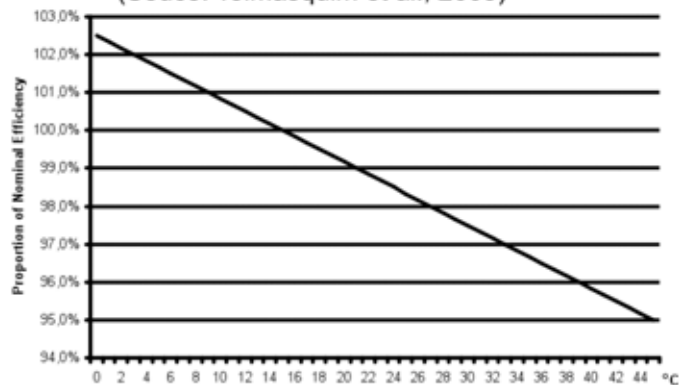
# Warmer Air and Water Impacts on Power Plant Efficiency and Capacity



Change in power as function of sea temperature at the Angra 2 Nuclear Power Plant  
(Source: Eletronuclear)



Influence of atmospheric temperature on the efficiency of gas turbines  
(Source: Tolmasquim et al., 2003)



Change in Power as function of temperature  
(Source: CEC-500-2006-034)

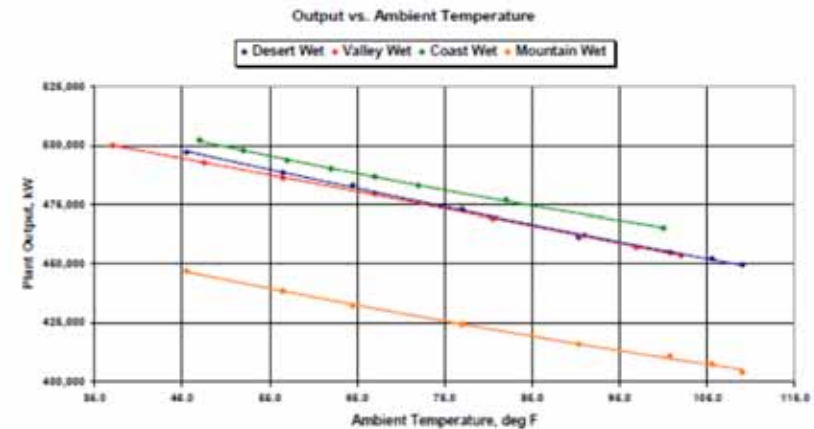


Figure 7. Output vs. ambient temperature—wet-cooled plants

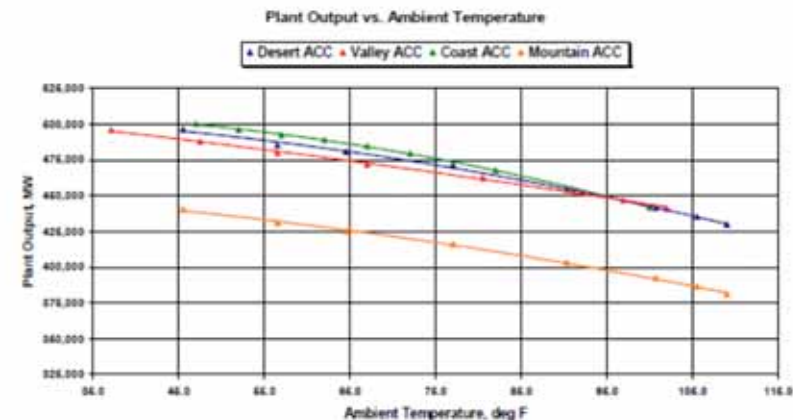
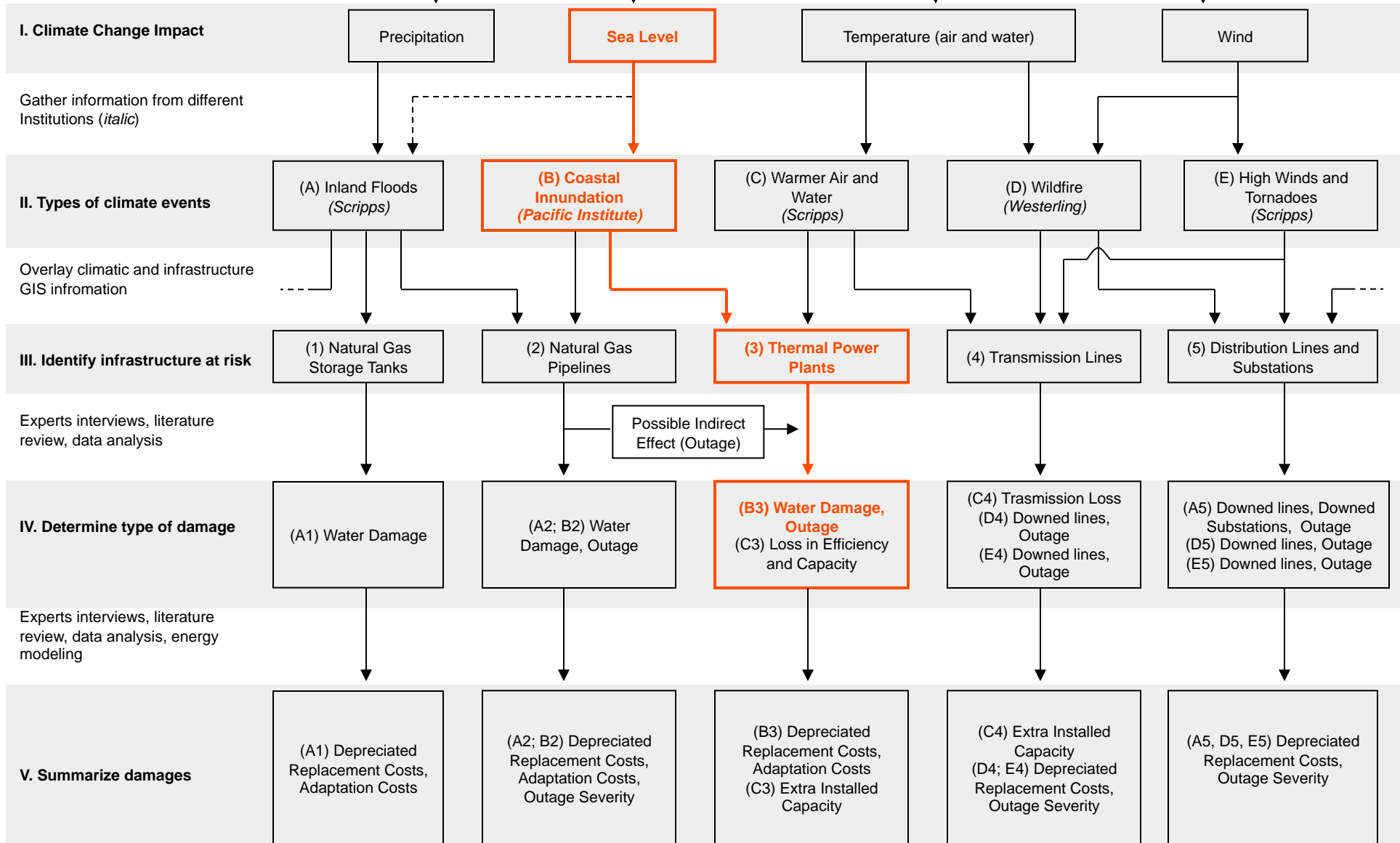


Figure 8. Output vs. ambient temperature—dry-cooled plants

# AOGCMs; Emission Scenarios

## Sea Level Example



# Sea Level Rise Impacts on Coastal Power Plants



- 30 Power Plants totaling over 10,000 MW vulnerable to a 100-year coastal flood with a 1.4 meter sea level rise.
- In some cases whole piece of infrastructure is at risk, whereas in other cases, only portions of structure are at risk (e.g., intake or other peripheral structures are exposed to flood risk).
- Information gathering:
  - What are the consequences (and costs) to each specific power plant that might be impacted?
  - What is the expected useful life span of each specific power plant?
  - Are there adaptation measures being taken (or proposed) to prevent (or reduce) damages from projected flooding? At what costs?



Power plants vulnerable to a 100-year coastal flood with a 1.4 meter sea-level rise

Data sources: USGS/Science Institution of Oceanography, California Energy Commission, CaGIL, EERI, [http://www.pacinst.org/reports/sea\\_level\\_rise](http://www.pacinst.org/reports/sea_level_rise)



(Source: Pacific Institute – [http://www.pacinst.org/reports/sea\\_level\\_rise/maps/](http://www.pacinst.org/reports/sea_level_rise/maps/))



## Misc. Thoughts on Damage Metrics and Data Needs

# Useful Metrics to Evaluate Second-Order Climate Risk to Energy Infrastructure



## I. Overlaid GIS Visualizations

- LBNL deliverable for this project.

## III. Direct Risk to Energy *Capacity* (MW or universal measure) or Energy *Output* (MWh or universal measure)

- LBNL deliverable for this project.

## V. Direct Risk to Infrastructure *Operational* and *Capital* Costs

- LBNL deliverable for this project? (pending data and other constraints)

## VII. Indirect Risk to Other Economic Activity (e.g., Outages?)

- Interesting future research topic?



# EXAMPLE: Financial Risk to Physical Capital (i.e. Lifecycle Cost Method)



Consider Catastrophic Sea-level Rise/Storm Surge Scenario for Vulnerable Infrastructure

Step 1: Estimate Baseline Present Value Replacement Costs

$$BCRC = \sum_{j=1}^{5,000} \sum_{i=2010}^{2050} \left( \frac{\Theta_{ij}}{(1+r)^{i-2010}} \right) \text{ where } \Theta_{ij} = \frac{BASERC_{ij}}{BASELIFE_{ij}}$$

Step 2: Estimate Climate-Related Present Value Replacement Costs

$$ADJRC = \sum_{j=1}^{5,000} \sum_{i=2010}^{2050} \left( \frac{\Delta_{ij}}{(1+r)^{i-2010}} \right) \text{ where } \Delta_{ij} = \frac{BASERC_{ij}}{ADJLIFE_{ij}}$$

Step 3: Determine Infrastructure Capital at Risk (no adaptation assumed)

$$AIC = ADJRC - BCRC$$

Step 4: Assume Some Level of Structural Adaptation?

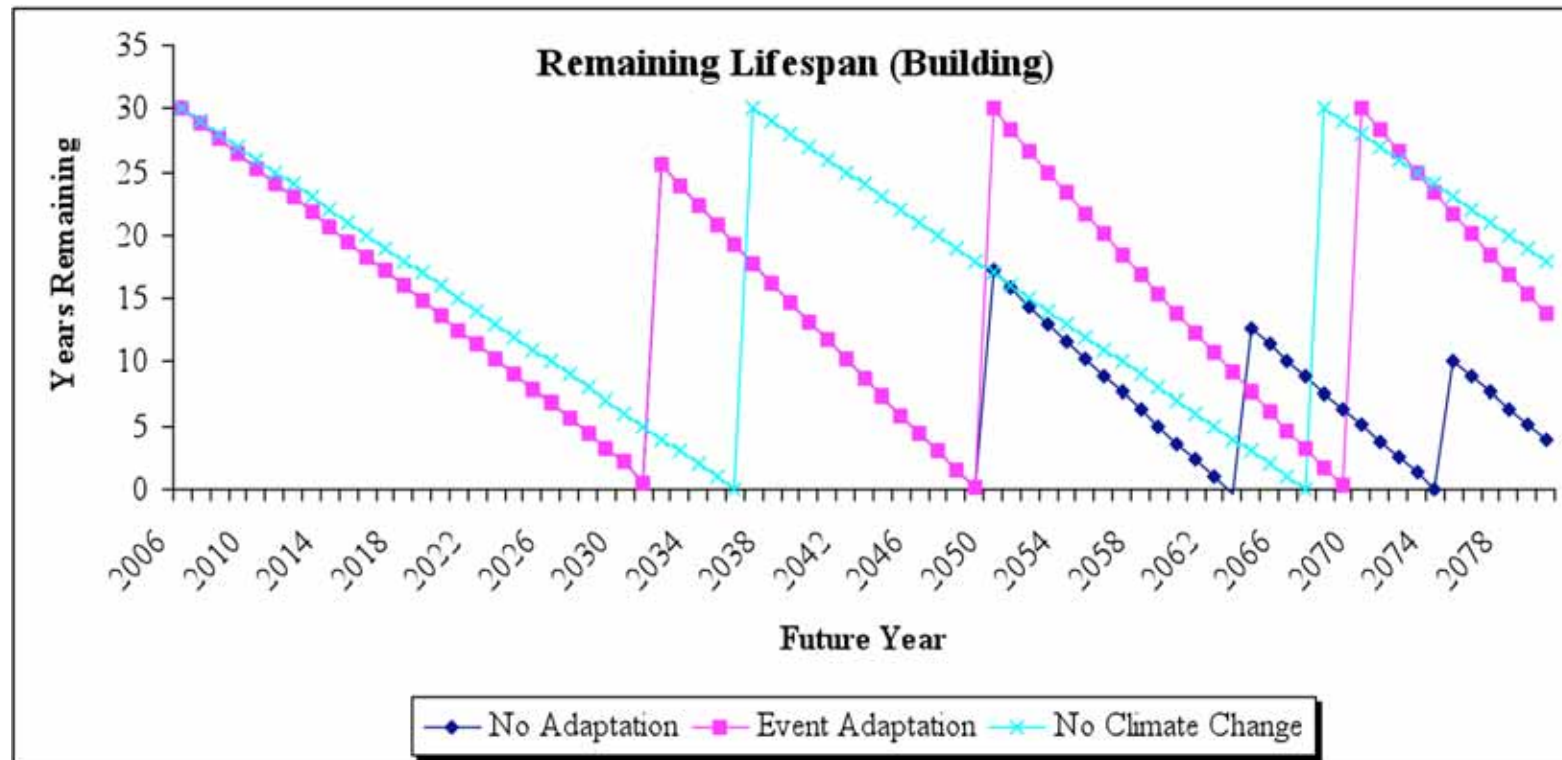
Step 5: Conduct Scenario/Monte-Carlo Simulations Varying the Inputs

# Estimation Caveats and Other Important Considerations



- I. Scaling and Aggregation Issues
  - A. Structure-by-structure?
  - B. County or regional aggregation?
  - C. Structure class (e.g., natural gas pipelines, power plant, etc.)?
  
- III. Uncertainty and Discounting Future Economic Risk
  - A. Communicating coupled modeling statistical uncertainty...
  - B. “Structural” uncertainty of impacts outweighs influence of discount rate choice (see Weitzman 2008).
  - C. Discount rate choice is still very critical in determining present value of climate impacts.
  
- V. Modeling Assumptions about Adaptation (see Perez 2009)
  - A. Energy Efficiency Standards (e.g., reducing water consumption)
  - B. Siting, building codes, and relicensing
  - C. Energy management and planning (e.g., optimally managing reservoirs)
  
- VII. Period of Analysis
  - A. Weak impacts signals in first few decades
  - B. Impacts signals become exponentially (or non-linear) stronger further out
  - C. Greater perceived risk influences forward-thinking adaptation decisions in earlier years

# AK EXAMPLE: Modeling Infrastructure Lifespans (with adaptation)



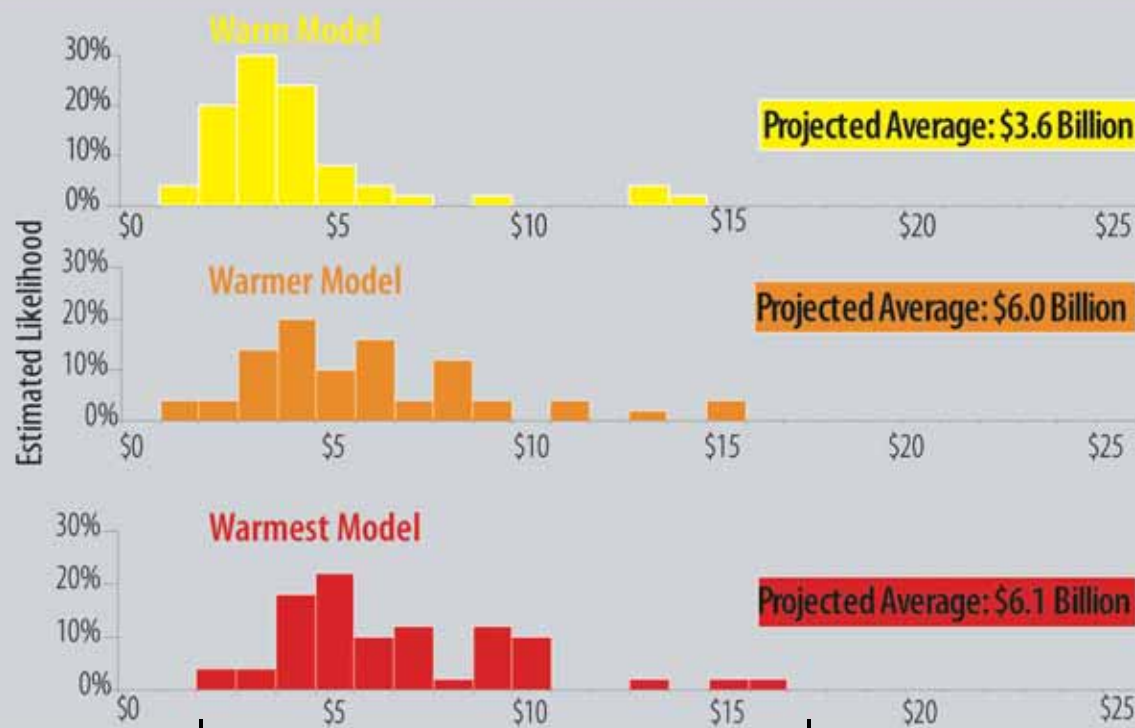
## Example Adaptation Scenario:

The Alaska model was programmed to rebuild/relocate structure at X% greater cost than average at point in time when Y% of structure's value is negatively impacted by climate change.

# AK EXAMPLE: Communicating Multiple Forms of Model Input Uncertainty



**Figure VII-2. Range of Additional Public Infrastructure Costs, 2006-2030, Adaptation Case**  
(In Billions of Dollars, Net Present Value)



Source: Larsen et al (2008)

*Three different AOGCMs*

*Monte-carlo Simulation (varied inputs)*



# General Information Needs

- I. Climate and Impact Variables
- III. Energy Infrastructure Variables
- V. Dispatch/Power Simulation Modeling Output?
- VII. Constructive Feedback from Technical Advisory Committee (TAC)



# Climate and Impact Variable Needs

<u>Variable</u>	<u>Units</u>	<u>Timescale</u>	<u>Spatial Resolution</u>
Monthly Ambient Temperature (high, low and average)	F or C F or C F or C	Current (AOGCM baseline) Historical data Projected (2050)	1/8 of Degree 1/8 of Degree 1/8 of Degree
Monthly Coastal Water Temperature (high, low and average)	F or C F or C F or C	Current (AOGCM baseline) Historical data Projected (2050)	1/8 of Degree 1/8 of Degree 1/8 of Degree
Monthly Freshwater Temperature (high, low and average)	F or C F or C F or C	Current (AOGCM baseline) Historical data Projected (2050)	1/8 of Degree 1/8 of Degree 1/8 of Degree
Wildfire Risk / Wildfire occurrence	lat/lon lat/lon lat/lon	Current (AOGCM baseline) Historical data Projected (2050)	1/8 of Degree 1/8 of Degree 1/8 of Degree
Wind Velocities (high, low and average)	m/s m/s m/s	Current (AOGCM baseline) Historical data Projected (2050)	1/8 of Degree 1/8 of Degree 1/8 of Degree
Local Sea-level (high, low and average)	lat/lon lat/lon lat/lon	Current (AOGCM baseline) Historical data Projected (2050)	Lat/Lon (continuous) Lat/Lon (continuous) Lat/Lon (continuous)
Monthly maximum storm surge level	lat/lon lat/lon lat/lon	Current Historical data Projected (2050)	Lat/Lon (continuous) Lat/Lon (continuous) Lat/Lon (continuous)

Source: Sathaye et al (2009)



# Energy Infrastructure Information Needs

<b>Variable</b>	<b>Units</b>	<b>Timescale</b>	<b>Spatial Resolution</b>
<i>Power Generator Location, Type, and Basic Engineering</i>	varies	Current	Lat/Lon (point)
Historical Production of electricity / power plant	energy	Historical Time series	power plant
Historical Fuel consumption / power plant	energy	Historical Time series	power plant
Quantitative relationship between air temperature and efficiency in each power plant, if possible, or aggregated by plant type - % / C or F			
Quantitative relationship between air temperature and capacity in each power plant, if possible, or aggregated by plant type - kW / C or F			
Quantitative relationship between cooling water temperature and efficiency in each power plant, if possible, or aggregated by plant type (for the case of wet cooling)			
Quantitative relationship between cooling water temperature and capacity in each power plant, if possible, or aggregated by plant type (for the case of wet cooling)			
Average Annual Maintenance Costs (aggregated by plant type?)	Dollars	Current	power plant
Power Plant Replacement Cost (aggregated by plant type?)	Dollars	Current	power plant
Powerplant age and useful lifespan	Years	Current	power plant
<i>Transmission Line Location, Type, and Basic Engineering</i>	varies	Current	Lat/Lon (continuous)
Heat dissipation (loss) due to conductor's resistance	%	historical average	system
Material's temperature coefficient of resistivity	$\Omega.m/K$	constant	system
Impacts of Fire on transmission lines	?		Lat/Long (ontinuous)
Average Annual Maintenance Costs (aggregated by line type?)	Dollars	Current	transmission line
Line Replacement Cost (aggregated by line type?)	Dollars	Current	transmission line
Trans. line age and useful lifespan	Years	Current	transmission line
<i>Distribution Line Location, Type, and Basic Engineering</i>	varies	Current	Lat/Lon (continuous)
Impacts of Fire on distribution lines	?		Lat/Long (ontinuous)
Average Annual Maintenance Costs (aggregated by line type?)	Dollars	Current	distribution line
Line Replacement Cost (aggregated by line type?)	Dollars	Current	distribution line
Dist. line age and useful lifespan	Years	Current	distribution line
<i>Pipeline Location, Type, and Basic Engineering</i>	varies	Current	Lat/Lon (continuous)
Average Annual Maintenance Costs (aggregated by line type?)	Dollars	Current	pipeline
Line Replacement Cost (aggregated by line type?)	Dollars	Current	pipeline
Pipeline age and useful lifespan	Years	Current	pipeline
<i>Fuel Storage Location, Type, and Basic Engineering</i>	varies	Current	Lat/Lon (point)
Average Annual Maintenance Costs (aggregated by storage type?)	Dollars	Current	storage facility
Facility Replacement Cost (aggregated by storage type?)	Dollars	Current	storage facility
Fuel storage facility age and useful lifespan	Years	Current	storage facility

Source: Sathaye et al (2009)



## Other Information Needs...

### III. Dispatch/Power Simulation Modeling Output?

- Would the CEC be able to provide power dispatch modeling output, if given agreed upon vulnerability scenarios?

### V. Constructive Feedback from Technical Advisory Committee (TAC)

- What is the most effective way to consolidate information from utility planners and engineers in order to determine the vulnerability of specific (or classes of) energy infrastructure?





## Selected References

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